DOM concentration, optical parameters and attenuation of solar radiation in high-latitude lakes across three vegetation zones

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Abstract

High-latitude lakes usually have a high penetration of light, due to their low productivity and low concentration of dissolved organic matter (DOM), but large variations in lake optical properties can be found within and between regions. We investigated the underwater light regimes in relation to DOM in 18 oligotrophic, high-latitude lakes across mountain birch woodland, shrub tundra and barren tundra in NW Finnish Lapland. DOM variability was measured by quantification of organic carbon and analysis of UV-visible absorbance and fluorescence spectra. In 12 out of 18 lakes > 1% of PAR reached the lake bottom while UV radiation exposure was more variable with 1% UVB depth ranging from 0.1 to > 12 m. Lakes located in barren tundra had highest transparency, lowest DOC concentration and lowest chromophoric DOM (CDOM) absorption (mean values: K_d PAR 0.3 m^{-1}, DOC 2.1 mg l^{-1}, a_{440} 0.4 m^{-1}), while lakes in shrub tundra and mountain birch forest were in general less transparent although still clear with a mean DOC concentration of 4.7 mg l^{-1} and CDOM absorption (a_{440}) of 1.4 m^{-1}. Solar attenuation and lake transparency were correlated with CDOM absorption (a_{440}), but the relationship was affected by the quality of organic matter and the concentration of DOC. Our survey emphasizes the importance of catchment type on DOM characteristics and lake optics and suggest that changes in vegetation zones will alter the overall aquatic light milieu in oligotrophic high-latitude lakes. We predict that even small changes in CDOM quality may largely change the UV radiation exposure of the studied high latitude lakes with likely consequences on biota while changes in PAR may have smaller biological effects in these shallow lakes that are already illuminated to the bottom even in the darkest systems.

Keywords: dissolved organic matter, high-latitude lakes, lake optical properties

Introduction

The concentration and optical qualities of dissolved organic carbon (DOC) and, in particular its chromophoric component, chromophoric dissolved organic matter (CDOM), play a major role in determining and understanding how lake ecosystems respond to disturbances such as global warming (Williamson *et al.,* 1999). They regulate the transmission of both photosynthetically active radiation (PAR; 400-700 nm) and ultraviolet radiation (UVR; 280-400 nm) (Scully & Lean, 1994; Morris *et al.,* 1995; Laurion, Vincent & Lean, 1997; Huovinen, Penttilä & Soimasuo, 2003; Bracchini *et al.,* 2006) and therefore contribute to defining the species composition in lakes (Rautio & Korhola, 2002), the ratio between auto- and heterotrophic producers (Jansson *et al*., 2000, Forsström, Roiha & Rautio, 2013), and the overall benthic and pelagic productivity (Karlsson *et al*., 2009).

The vegetation in the catchment, catchment to lake ratio, and the productivity of the lake have a prominent impact on the concentration and composition of DOM. In small oligotrophic lakes with low chlorophyll- a concentration and large catchment areas a high proportion of carbon is derived from terrestrial and wetland sources dominated by higher terrestrial plant productivity (Bade *et al*., 2007). The organic carbon leaching from forests and wetlands constitute mainly of slow-degrading and nutrient poor material dominated with humic and fulvic constitutes (McKnight & Aiken, 1998; McKnight, Aiken & Smith, 1991; McKnight *et al.,* 1994) that are the most important components in absorbing solar radiation (Morris *et al.,* 1995; Ferrari & Dowell, 1998). CDOM can also be generated within the water body by decomposition of phytoplankton or higher aquatic plant tissues (autochthonous input) scarce in fulvic and humic constituents (Benner, 2003) resulting in deep penetration of solar radiation (McKnight *et al*., 1994). UV-visible absorbance and fluorescence spectroscopy provide information on the origin and chemical structure of DOM: autochthonous molecules of CDOM have a smaller absorbance for a given wavelength than allochthonous molecules and show strong fluorescence between the wavelengths 293-308 nm (with a secondary peak around 360 nm), whereas allochthonous humic and fulvic materials fluoresce at longer wavelengths (McKnight, Aiken & Smith, 1991; McKnight *et al.,* 2001; Belzile *et al.,* 2001).

Due to climatic warming, higher precipitation and associated vegetation and soil property changes in lake catchment areas, higher inputs of terrestrial DOMh to high-latitude lakes are expected (Vincent, Laurion & Pienitz, 1998; Sommaruga *et al*., 1999; Pienitz & Vincent, 2000; ACIA, 2005; Meehl *et al.,* 2007). For other northern lakes, this scenario of increasing DOM is not applicable since some areas are showing opposing trends of drought and cooling (Pienitz *et al.,* 2004; Fallu *et al.,* 2005; Rolland *et al.,* 2008). Whatever the direction of change, climatic change will not only alter the amount of DOM transported to high-latitude lakes, but may also change its chemical composition and absorption characteristics, mainly because of modifications that occur in the catchment vegetation (Curtis, 1998). These lakes already have low DOC concentrations and even small changes in CDOM concentration will alter the PAR and UVR penetration depth drastically (Vincent, Laurion & Pienitz, 1998; Rautio & Korhola, 2002; Bracchini *et al.*, 2006). Despite the fundamental floristic differences between different vegetation zones across and near the northern tree line, the influence of the catchment type on DOM composition at high latitudes has rarely been addressed.

In this study, our objectives were 1) to evaluate how lakes in different vegetation zones differ from each other in their catchment features, DOM parameters and algal biomass, and 2) how these contribute to defining the attenuation of solar radiation in lakes. We measured the variability in DOM concentration, optical parameters and in the attenuation of solar radiation from 18 high-latitude lakes along a transect from the northern treeline to barren tundra in NW

Finnish Lapland, including three distinct vegetation zones. We hypothesized that lakes within each vegetation zone are more close to each other in their DOM variables than lakes between zones, which would allow estimating how the lake optics and carbon dynamics will change with climate change and moving vegetation zones. Information on lake optics and DOM characteristics has previously been reported from the region only for one lake and some small ponds (Rautio, Mariash & Forsström 2011; Roiha et al., 2012). This study was further carried out to enhance knowledge on the quantity and quality of DOM and to assess the applicability of DOM indices in high-latitude lakes. Because high-latitude lakes are often driven by benthic production that relies on high transparency (Rautio & Vincent, 2006; 2007; Hessen & Leu, 2006; Karlsson & Säwström, 2009), and the majority of unproductive lakes are thought to be light rather than nutrient limited (Karlsson *et al.*, 2009), it is crucial to understand the coupling between DOM, solar attenuation and phytoplankton, and how this might change with respect to global change.

Materials and methods

Study area and sampling

A set of 18 small to medium size high-latitude headwater lakes were sampled between August 16 – 26 in 2004, during the autumn overturn. The study lakes are located about 450 km north of the Arctic Circle (Figure 1) in NW Finnish Lapland (68-69°N, 20-22°E) and over a range of different bedrock types. Four lakes are situated below the tree line (approx. 600 m a.s.l.) in the mountain birch woodland (MBW), ten lakes in catchment areas with mires and shrubs (ST), and four lakes in catchment areas with barren, rocky ground (BT), following the vegetation zones for this region (Virtanen & Eurola, 1997). The lakes were selected to cover large gradients in altitude, catchment and bedrock type, and optical characteristics. The study area lies in the transition zone between the North Atlantic oceanic climate and the Eurasian continental climate. Above the treeline, the vegetation mainly consists of low dwarf shrubs, mosses, grasses and sedges. The catchment areas of the lakes are not impacted by direct human activities. Table I summarizes the main environmental information of the lakes.

For this study, all the lakes were visited once, and water samples were taken from a depth of 1m with ajj water sampler (Limnos Ltd, Turku, Finland). In addition, three of the deepest lakes were sampled from deeper water layers (Table I). Water temperature, pH and conductivity were all measured *in situ* using a YSI 63 pH and conductivity instrument (YSI Incorporated, Yellow Springs, USA). Alkalinity, ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_{3+2}-N), orthophosphate phosphorus (PO_4-P), total phosphorus (TP), total nitrogen (TN), silica (SiO_2-S), and turbidity were analyzed in the Lapland Regional Environmental Centre using the standard methods of the National Board of Waters in Finland. DOC concentration was analyzed as non-purgeable organic carbon with Shimadzu TOC 5000A and chlorophyll *a* according to Jefferey and Humphrey (1975) at the Lammi Biological Station. Phytoplankton samples, also taken at 1 m depth, were preserved with acid Lugol's solution and analyzed with an inverted microscope according to Utermöhl (1958). Phytoplankton biovolumes were calculated from cell densities based on measurements of the size of the species and the approximation of the shapes to geometrical figures. Biomass was calculated from measured algal volumes assuming a density of 1.

DOM analyses and light measures

DOM absorbance spectra were measured from filtered lake water as in Forsström, Roiha & Rautio, 2013. The spectral slopes of various range (275 to 295, 350 to 400 and 300 to 650 nm), as well as the slope ratio S_R ($S_{275-295}$ to $S_{350-400}$) were used to describe DOM quality (Stedmon, Markager & Kaas, 2000; Helms *et al.*, 2008). In addition, we used the approach introduced by Loiselle *et al.* (2009), and calculated the spectral slope for each 20 nm interval between 200 and 500 nm and plotted the resulting slopes by the center wavelength of each range to create spectral slope curves as function of wavelength, (S(λ), nm^{-1}). The regression coefficients (r^2) were, in general, greater than 0.99, and the addition of a constant to the regression model, as suggested by Stedmon, Markager and Kaas (2000) did not result in a better fit. We used S280 and S390 as indicators of algal or humic substances (Loiselle et al. 2009). Additionally, absorption at 320 and 440 nm is used as a measure of CDOM concentration and color and DOC specific a_{320} as a proxy of the degree of DOM color. Specific UV absorbance (SUVA) at 254 nm was calculated as the absorbance at 254 nm divided by the DOC concentration to estimate variation in landscape features and, hence, in the source of carbon (Weishaar *et al.,* 2003). For comparison, CDOM absorbance was measured from one allochthonous (water taken from a nearby bog) as well as one autochthonous (a *Scenedesmus* sp. culture) source.

From each sample, a synchronous fluorescence spectrum (SFS) was measured with a Cary Eclipse fluorescence spectrophotometer (Varian Inc., USA) as employed by Belzile, Gibson and Vincent (2002). The wavelength difference between excitation and emission beams was 14 nm. Fluorescence scans were standardized to quinine sulphate units (QSU) using a standard of quinine sulfate dehydrate (Sigma-Aldrich no. 22640) dissolved in 0.02 N sulfuric acid and corrected for the absorption within the sample (inner filter effect) according to McKnight *et al.* (2001). To characterize DOM composition, we calculated integrated areas of different wavebands (Retamal *et al.,* 2007): low molecular weight compounds (LMW, emission range 280-323 nm), medium molecular weight compounds (MMW, emission range 324-432 nm) and high molecular weight compounds (HMW, emission range 433-595 nm) and used their relative proportion (Lλ/Hλ and Mλ/Hλ) to describe CDOM composition. In addition, humification index (HI), a measure of the degree of polycondensation and humification of

DOM, was calculated according to Kalbitz, Geyer and Geyer (1999) from synchronous fluorescence scans as a quotient of fluorescence intensity at 470 and 360 nm.

Transmission of downwelling UV irradiance (at 320, 340 and 380 nm) and PAR was measured with a PUV500 radiometer (Biospherical, San Diego, USA) *in situ* at each site. Diffuse attenuation coefficients (K_d) of UVR and PAR in the water column were obtained from the slope of the linear regression of the natural logarithm of down-welling irradiance (E_d) versus depth (Z), $\ln(E_{d(Z)}) = -K_d Z + c$, where the constant $c = \ln(E_{d(0-)})$, with $E_{d(0-)}$ being the irradiance just below the water surface.

Statistical analyses

Differences in catchment features, DOM parameters and algal biomass among vegetation zones were tested using ANOSIM followed by pairwise t-tests to identify differences. Data were normalised and Euclidian distances were used to generate resemblance matrix. A similarity percentage analysis (SIMPER routine) was used to assess the percentage contribution of each variable to the observed dissimilarities among vegetation zones. Principal component analyses (PCA, normalized values, Euclidean distances) with segmented bubble plots were used to visualize vegetation zones and associated statistically most important environmental variables that likely regulate light attenuation. Lake Kilpisjärvi was omitted from these analyses due to its large size that was two magnitudes of orders larger in catchment area, lake area and depth than the other lakes making it an outlier for most variables.

BIOENV analyses routine were used to identify which environmental variables or combination of variables (altitude, catchment to lake ratio, catchment slope, turbidity, chl-a, phytoplankton biomass, DOC, SUVA, HI, a_{440}, $S_{300-650}$, Lλ/Hλ, Mλ/Hλ, S280, %LMW, %MMW, %HMW) best explained the changes in light attenuation (K_d *PAR*, K_d *320* nm) and transparency (transparency ratio) when lake data from different vegetation zones were pooled.

Other environmental variables were omitted from the analyses due to their high Pearson correlation ($r > 0.90$) with some included variables or because of missing values. The lakes Korsajärvi and Koddojavri were excluded as some of their DOM variables were outliers. The statistical analyses were carried out in Primer (version 7) and JMP (version 11). A significant level $\alpha = 0.05$ was used for all statistical tests.

Results

Catchment and morphological parameters

With the exception of Lake Kilpisjärvi (lake area 3710 ha, max depth 57 m), the MBW lakes were small (lake area 5-20 ha) and shallow (max depth 2 m). ST lakes had a relatively high range of size and depth (lake area 1-100 ha, max depth 4-24 m), whereas BT lakes were amongst the smallest (lake area 1-10 ha), but two of them were relatively deep (max depth 9 and 12 m. Ratio of catchment to lake area ranged from 3 to 11 in MBW, from 7 to 42 in ST and from 4 to 32 in BT. Mean slope of the catchment was generally highest in ST (Table I).

According to ANOSIM, there was a difference in catchment and morphological parameters according to vegetation zones ($R = 0.412$; $p = 0.004$) with all pairwise comparisons ($p < 0.05$ for all). Catchment slope contributed to explaining the variability between all zone comparisons (27-48%) while other important variables were altitude (39-62%) and catchment to lake ratio (26-29%). Figure 2a shows the PCA ordination of the lakes with the variability in catchment slope and catchment to lake ratio in different lakes.

Temperature, water chemistry and algal biomass

Due to their shallowness, the majority of lakes (11) were isothermal during the sampling. Lake water temperature varied between 5.9 and 11.9 ºC being highest at lowest altitudes. Conductivity had highest range in ST, between 0.7 and 4.3 mS m^{-1}. The pH of three lakes, two from MBW and one from BT, was < 6 (Ristijärvi, Koddojärvi, 1009) and the rest between 6.7 and 7.8. Alkalinity averaged 0.125 mmol l^{-1}. All lakes had low nutrient concentrations (inorganic nutrients mainly below the detection limit, total P 3-13 µg l^{-1} and total N 71-410 µg l^{-1}) and low turbidity (< 1.0 FNU), with highest values generally measured from MBW. Chlorophyll *a* concentration varied between 0.2 µg l^{-1} and 2.4 µg l^{-1} and phytoplankton biomass was low (less than 0.5 mg l^{-1}) in all the study lakes. Only in the deepest lake (Kilpisjärvi) of the three that were sampled from two different water layers, was chlorophyll *a* markedly lower in the deeper water layer compared to the 1m depth (Table I). Most lakes were dominated by chrysophytes (Chrysophyceae), but in a few lakes the dominating algal group was green algae (Chlorophyceae), cryptophytes (Cryptophyceae) or dinoflagellates (Dinophyceae). Dinoflagellates were most common in MBW lakes with high DOC and color (Korsajärvi, Koddojärvi and Ristijärvi) (L. Forsström, unpublished data).

ANOSIM identified two groups separating the lakes above (combined zones ST and BT) and below the tree line (MBW) in water chemistry (R = 0.317; p = 0.003) and algal biomass (chl-a and biomass) (R = 0.343; p = 0.003). Figure 2b shows the distribution of Chl-a and phytoplankton biomass in lakes from different catchment areas.

DOC concentration and DOM characteristics

DOC concentration varied from 1.5 to 16.2 mg l^{-1} (Table II). Average DOC concentration was 9.7 mg l^{-1} in MBW, 3.0 mg l^{-1} in ST and 2.1 mg l^{-1} in BT. CDOM absorption coefficient at 320 nm ranged from 1.0 to 61.0 m^{-1} (mean values: MBW 26.3 m^{-1}, ST 4.0 m^{-1}, BT 3.3 m^{-1}). CDOM absorption coefficient at 440 nm, an indication of color, varied from 0.1 to 9.4 m^{-1}, with only two MBW lakes having values > 1.1 m^{-1}. DOC specific absorptivity varied from 0.4 to 3.8 mg $^{-1}$ m^{-1}. $SUVA_{254}$, a parameter indicating DOM quality, varied from 0.3 l mg^{-1} m^{-1} in barren tundra to 6.2 l mg^{-1} m^{-1} in mountain birch forest. Average $SUVA_{254}$ was 2.9 l mg^{-1} m^{-1} in MBW, 1.4 l mg^{-1} m^{-1} in ST and 1.0 l mg^{-1} m^{-1} in BT. The spectral slope coefficient, S, had the smallest variation (0.014-0.02 nm^{-1}) when calculated for the shortest wavelengths; 275-295 nm. Slopes for 300-650 nm and 350-400 nm had relatively similar ranges of variation (0.006-0.017 and 0.005-0.017 nm^{-1}, respectively), but it is noteworthy that S for these wavelength bands could not be calculated for all the study lakes: the BT lakes 1009 and Kuorroladdu had very low absorption, causing excessive interference around 350 nm, the area where the light source switches from UV to visible light. As the interference absorption at 320 nm could not be reliably measured, the spectral slope for these two lakes was calculated between 385-650 nm. In addition, sample from Lake Koddojavri (MBW) should have been diluted for reliable measurements for the shortest wavelengths (< 300 nm).

In addition to traditional absorption slopes, spectral slope curves, S(λ), were used to describe differences in CDOM (Table II). Spectral slope values showed a large variation over the considered wavelengths (0.004-0.100 nm^{-1}). S_{280}, an indication of algal-derived DOM (Loiselle *et al.* 2009) was lowest in MBW lakes (mean 0.017 nm^{-1}, min 0.014 nm^{-1}, max 0.018 nm^{-1}) and highest in BT lakes (mean 0.019 nm^{-1}, min 0.016 nm^{-1}, max 0.025 nm^{-1}). S_{390}, associated with fulvic acids (Loiselle *et al.,* 2009), was lowest in BT lakes (mean 0.013 nm^{-1}, min 0.009 nm^{-1}, max 0.017 nm^{-1}) and highest in MBW lakes (mean 0.017 nm^{-1}, min 0.017 nm^{-1}, max 0.017 nm^{-1}). Shape of the spectral slope curve varied considerably between lakes from different vegetation zones (Figure 3a). Curves from the two highly-colored MBW lakes, Korsajärvi and Koddojavri, had high resemblance to bog-water taken from Markkinasuo (68°29’N, 22°16’E), a bog located close to the study region. These lakes show highest values in spectral slopes at around 350-390 and only a small peak at S_{280} with a maximum at around S_{390}. In contrast, ST and BT lakes show similarities to a curve measured from a *Scenedesmus* phytoplankton culture, with a high peak at S_{280}. However, at S_{390} they were closer to the DOM from bog than from phytoplankton with a relatively high peak at S_{390}.

Synchronous fluorescence scans enabled further characterization of CDOM quality and identification of the CDOM sources, and showed differences between the study lakes (Figure 3b). All lakes showed a fluorescence peak around 280-300 nm, indicating autochthonous CDOM, only the intensity varied reflecting concentration of CDOM in lakes from different vegetation zones. In all but two barren tundra lakes (1009 and Stuorralampi) the highest relative contribution of fluorescence was observed in the area of medium molecular weight, indicative of components originating from allochthonous processes. The highest share of LMW fluorescence, around 25% of total fluorescence, was found in lakes Kuorroladdu (MBW) and Somaslompolo (ST), two lakes with very high transparency. The highest MMW fluorescence, close to 50% of total fluorescence, was found in Kuorroladdu (BT), Peeralampi (ST) and Kilpisjärvi (MBW), whereas the highest HMW fluorescence was measured from 1009 (BT) and Stuorralampi (BT). $L\lambda/H\lambda$ varied between 0.3 and 1.0, whereas $M\lambda/H\lambda$ varied between 0.9 and 2.1. Both ratios had a highest range in the barren tundra. The humification index (HI) ranged from 0.5 to 0.9 (Table II). Lake Koddojavri (MBW) showed such a high inner-filter effect (Lakowicz, 2006), that it was omitted from the SFS results.

In lakes where sampling was done from two different depths, DOC concentration and a_{CDOM} were lower or similar and DOC-specific a_{CDOM}, a^*_{320}, was higher in deeper samples compared to samples taken from the 1m depth (Table II). In Kilpisjärvi (MBW) and Saanajärvi (ST), $SUVA_{254}$ was higher in the hypolimnion than in the epilimnion, but in Mallajärvi (ST) it was the opposite. The relative amount of LMW fluorescence and $L\lambda/H\lambda$ was always lower and HI higher in samples taken from the hypolimnion than in the epilimnion, but other indicators of DOM quality did not have an even trend$S(\lambda)$ curves showed only minor differences when calculated from different depths (data not shown).

Several variables in the DOM dataset were highly correlated with each other, with highest correlations observed between a_{320} and a_{440} (Pearson's correlation r = 0.988), $S_{275\text{-}295}$ and S_{290} (r = 0.983), $S_{300\text{-}650}$ and S_{390} (r = 0.960), $S_{350\text{-}400}$ and S_{390} (r = 0.934) and a^*_{320} and SUVA (r = 0.910). The DOM variables DOC, SUVA, SR, HI, a_{440}, S_{280}, $S_{300\text{-}650}$, Lλ/Hλ, Mλ/Hλ %LMW, %MMW and %HMW were selected for ANOSIM which identified statistical differences in them according to vegetation zones (R = 0.496; p = 0.008) As for catchment parameters, all vegetation zones were different from each other (pairwise comparisons; $p < 0.05$ for all). a_{440} (24-34%), DOC (25-32%) and SUVA (22-27%) explained the variability between lakes below and above the tree line while S_{280} (45%) separated the ST and BT lakes from each other. The distribution of a_{440} and S_{280} is shown in Fig. 2c.

PAR and UV attenuation

The transparency over the PAR waveband (400–800 nm) was generally high, with K_d values < 0.8 m^{-1} for all but two MBW lakes (Korsajärvi 2.6 m^{-1} and Koddojavri 2.4 m^{-1}) (Table III). In 12 out of 18 lakes, > 1% of PAR reached the lake bottom. K_d at 320 nm, representing attenuation of UV-B radiation, varied between 3.1 and 70.4 $m^{-1}$for the MBW lakes, between 1.2 and 7.7 m^{-1} for ST lakes, and between 0.3 and 5.9 m^{-1} for BT lakes. In two BT lakes (1009 and Stuorralampi) more than 1% of UV-B radiation reached the lake bottom and the average depth of 1% at 320 nm was 2.4 m. The inferred attenuation depth of UV ($Z_{UV1\%}/Z_{max}$) expressed as a proportion of lake maximum depth varied from 3% to 100%, and was more than 10% in 10 lakes. The transparency ratio (1% depth of 320 nm UV relative to the 1% depth of PAR) varied between 3.5% and 50.9%, the average being 12.8%. Because K_d320 and 1% UV-B depth as well as K_dPAR and 1% PAR depth were highly correlated (r > 0.9), the 1% depth values were excluded from the ANOSIM. The vegetation zones separated from each other (R= 0.384, p = 0.001) but according to SIMPER only the shrub tundra (ST) zone was different from the two other while lakes below tree line (MBW) and on barren tundra (BT) were similar. The high variability within MBW and ST lakes (Fig. 2d) and the low number of lakes in these zones prevented SIMPER to separate them from each other. K_{d320} explained most of the variability between MBW and ST lakes (48%) while transparency ratio explained the difference between ST and BT lakes (96%).

The BIOENV analyses identified a440 as the most important environmental variable explaining light attenuation (K_d320 and K_dPAR) and transparency of the lakes studied (Table IV, Fig. 4). Alone it explained 77% of the data variability but when considered with different combinations with S_{380}, S_{280}, DOC, SUVA and HI these parameters explained more of the variability than a_{440} alone. However, these supplementary variables alone explained clearly less of the light parameters than a_{440} (Table IV).

Discussion

Our data for high-latitude lakes from northern Finland show that DOM has a major influence on underwater UV-B and PAR attenuation and transparency ratio. Absorbance at 440 nm (a_{440}) with spectral slope at 390 nm (S_{390}) explain nearly 90% of the optical variability between lakes while S_{280}, DOC, SUVA and HI also importantly contributed to defining the light milieu in the lakes. The dominant importance of a_{440} is consistent with observations from other high latitude or mountain regions (Laurion, Vincent & Lean, 1997; Laurion *et al.,* 2000; Belzile, Gibson & Vincent, 2002) while S_{390} is an indicator of fulvic acids of DOM (Loiselle *et al.*, 2009) that contribute to increasing DOM color and therefore influence PAR and UV attenuation.

Landscape control of lake optics

Although our study lakes were located in a relatively small region of NW Finland, the results demonstrate that high-latitude lakes are not a cohesive group of lakes. Despite their globally low levels of some common features, such as low nutrient levels, low phytoplankton biomass and high transparency, they display high variability in catchment properties, lake morphology and DOM characterization depending on the lake's location in the landscape. Such variability in especially morphological features is typical for postglacial lakes (Pienitz, Doran & Lamoureux 2008). Our analyses indicated that the lakes from below the tree line, from shrub tundra and from barren tundra separate from each other according to their catchment variables and DOM composition. Similar landscape control on lake physical and chemical parameters have been earlier documented for the same geographical area but using a different set of abiotic and biotic variables (Rautio 2001; Mariash *et al.*, 2011; Roiha *et al.*, 2012). The most unified group of lakes based on several variables was shrub tundra, despite the fact that it contained the highest number of lakes. The observed deviation from the other zones was mainly explained by catchment slope, catchment to lake ratio, a_{440}, K_d and transparency ratio. Other important factors were the ratio of catchment slope, DOC, SUVA, S_{280} and $S_{300\text{-}650}$. Taken together these factors indicate that DOM optics were different in different vegetation zones and imply that changes in zone locations will likely cause shifts in the light milieu of the lakes and subsequently in their productivity (Pienitz & Vincent, 2000; Karlsson *et al.*, 2009).

The variation in DOC has commonly been shown to be closely linked with UV and PAR attenuation (Schindler *et al.*, 1996) and to be controlled by catchment area properties, lake morphometry and the relationship between catchment area to lake surface area (Williamson *et al.*, 1996; McKnight *et al.*, 1997; Sommaruga *et al.,* 1999; Bukaveckas & Robbins-Forbes, 2000; Xenopoulos *et al.,* 2003; Winn *et al.,* 2009). DOC concentration of our study lakes was low (median 2.7 mg l^{-1}) and the range was comparable to results reported from the Adirondack Mountain Regions (Bukaveckas & Robbins-Forbes, 2000) and from Alaska and the NE USA region (Morris *et al.,* 1995). In our study, DOC contributed to light attenuation as a supplementary variable (with SUVA and HI) but no significant correlation was found between lake morphometric properties, size or topography of the catchment area and DOC. The concentration of DOC neither varied significantly among vegetation zones but here it is important to keep in mind the relative small number of lakes per zone that most likely restricted identifying some associations. However, DOC was negatively correlated with altitude ($r = -0.54$), which can be related to altitudinal changes in catchment properties (e.g. less organic soils at higher elevations and variation in vegetation along an elevation gradient). A similar relationship between DOC and altitude has been reported in other comparable studies (e.g., Sommaruga *et al.,* 1999).

The relative importance between DOC and DOM parameters

The present study supports the conclusion that DOM is better than DOC in explaining differences in light attenuation in low DOC lakes of high-latitude and high-altitude areas (Morris *et al.,* 1995; Laurion *et al.,* 2000; Sommaruga, 2001). The spectral irradiance across the PAR and UV ranges was tightly controlled by a_{440} that is often used as an indicator of CDOM color. Because a_{440} and a_{320} were highly correlated ($r = 0.988$) we used only a_{440} as an explanatory variable in our analyses but it is good to keep in mind that absorption in general provides an excellent indicator of spectral attenuation and can be used as an index of K_d when direct spectral measures are not possible. Absorbance measures are also faster, easier and cheaper to make than any of the other DOM measures, including analyses of DOC concentration and calculations of most spectrophotometric and spectrofluorometric data variables.

Spectral attenuation correlated also with DOC but the relationship was not always predictable. In general, there was a positive correlation between DOC and K_dPAR ($r = 0.707$), and DOC and K_d320 (r = 0.692), but the relationship was not always linear. Lake Vuobmegasvarri (BT) and Lake Somaslompolo (ST) had the same DOC concentration (2.5 mg l^{-1}), but the measured K_d320 differed considerably, the former lake having a relatively high K_d320 (5.9 m^{-1}) leading to a 1% UV penetration depth of only 0.8 m, whereas the latter lake had a relatively low K_d320 (1.2 m^{-1}), with a 1% UV penetrating to 3.8 m. These differences in the solar attenuation were likely due to differences in CDOM composition. SUVA and a^*_{320} indicated that DOC of Lake Vuobmegasvarri is more terrestrial compared to Lake Somaslompolo (SUVA: 2.2 and 0.6 mg^{-1} m^{-1}, a^*_{320} 2.1 and 0.5 m^{-1}, respectively). Same difference is seen in the ratio between S_{280} to S_{390}. HI was slightly lower and the relative proportion of LMW fluorescence higher in Somaslompolo, reflecting a higher contribution of autochthonous carbon. Both lakes are closed-basin lakes, but while the catchment area of Vuobmegasvarri is mostly covered by various dwarf shrubs, grasses and sedges, the catchment of Somaslompolo consists mostly of esker and rock. Somaslompolo is also much larger and deeper, which means that all material entering the lake from the catchment is mixed into a larger volume of water.

Similarly, Lake Vuobmegasvarri (BT) and Lake 613 (MBW) with relatively comparative UV attenuation behavior (K_d320 5.9 and 6.3 m^{-1}, respectively), had very different DOC concentrations (2.6 and 6.9 mg l^{-1}, respectively). Located in the barren tundra Lake Vuobmegasvarri does not have a high DOC concentration per se but this carbon seems to be dominated by terrestrial compounds as suggested by the relative high values of a440, a^*_{320}, and SUVA. Lake Vuobmegasvarri is small and shallow and has the highest catchment to lake area of the whole data set likely explaining the DOM composition efficient in solar absorbance.

The lack of correlation between DOC, DOM and light parameters is consistent with earlier observations. When comparing different biomes, Jaffé *et al.* (2008) did not find a correlation between DOC and any of their DOM quality parameters, and concluded that variations in DOM quality were not necessarily associated with DOC concentration. The lack of correlation is in some lakes also related to iron (Fe). Fe concentrations > 2mg l^{-1} are known to have an effect on the UV absorbance of DOC (Weishaar *et al.,* 2003). Fe was not analysed during this study, but previous work from the same area indicate low Fe concentrations (mean 0.14 mg l^{-1} for mountain birch woodland (n = 25) and 0.04 mg l^{-1} for barren tundra (n = 8)) (Korhola, Weckström & Blom, 2002) that should not influence UV absorbance.

Phytoplankton as light attenuator

Concentration of Chl-*a* was lower in our study lakes compared to other studies dealing with water column optics of high-altitude or high-latitude lakes (Morris *et al.,* 1995; Bukaveckas & Robbins-Forbes, 2000; Laurion *et al.*, 2000). Even with somewhat higher chlorophyll concentrations, the role of Chl-*a* in light attenuation has proved to be low in some comparable studies (Morris *et al.,* 1995; Bukaveckas & Robbins-Forbes, 2000), and no correlation between K_dPAR and Chl-*a* was found in our study either. Chl-*a* explained only 39% of light variability. Laurion *et al.* (2000) found a weak but significant correlation between K_dPAR and Chl-*a* (but not between K_d320 and Chl-*a*) in lakes from the Alps and Pyrenees, but those lakes had, in general, higher Chl-*a* concentrations than in our data (mean Chl-*a* 1.6 µg l^{-1} vs. 0.7 µg l^{-1}, respectively). Our Chl-*a* samples were only taken from one depth (1 m), but since most lakes were isothermal during the sampling, we consider this one sample to be representative of the whole water column.

The weak but significant positive correlation between Chl-*a* and DOC (r = 0.16) and phytoplankton biomass and DOC (r = 0.29) found in this study, likewise in lakes situated in the Adirondack area, USA (Bukaveckas & Robbins-Forbes, 2000) may result from a reduction of photoinhibition and an increase of nutrients associated with higher levels of DOC. The finding is interesting in respect to current climate change scenarios. Taken in conjunction with some whole-lake experiments (e.g., Carpenter *et al.,* 1998) these studies suggest that increasing DOC concentrations expected at high-latitudes due to global warming and associated vegetation shifts can lead to higher accumulation of algal biomass. However, other studies have not found a similar relationship (Sommaruga *et al.,* 1999), and a simple measure of Chl-*a* does not give any information on changes in species composition or productivity. Our study lakes had very diverse and differing phytoplankton communities (L. Forsström, unpublished data), and it is likely that they will react differently to possible changes. A mesocosm study conducted in the same area showed a decrease of primary production, but an increase of the proportion of mixotrophic algae when DOC was added (Forsström, Roiha & Rautio, 2013). Bukaveckas and Robbins-Forbes (2000) concluded that DOC might be the major factor explaining the variation of primary productivity in lakes that are remotely situated from human induced eutrophication, but more studies are needed to assess the role of DOC for primary production in these areas.

Current light climate and prospections for future

Light penetrated deeply in the studied lakes. Attenuation of visible light varied in our data set from the values previously reported for the clearest inland waters at high latitudes or high altitudes ($K_d < 0.2$ m^{-1}) (Kirk, 1994; Morris *et al.,* 1995; Bukaveckas & Robbins-Forbes, 2000; Laurion *et al.*, 2000) and for values reported for highly colored lakes located in boreal and alpine regions ($K_d > 2.0$ m^{-1}) (Lindell, Gráneli & Tranvik, 1996; Ask *et al.*, 2009). The average depth of 1% at 320 nm (2.4 m) is higher than the average calculated for sub-alpine lakes (1.9 m), but lower than the average for alpine lakes (8.1 m) (Rose *et al.,* 2009). The average transparency ratio (12.8%) was close to the average calculated for sub-alpine lakes (12.6%), but the ratio in Lake 1009 (50.9%) was close to the highest values reported in alpine lakes (Rose *et al.*, 2009). In contrast to alpine lakes, our lakes are very shallow, and in several study lakes the UV exposure compared to lake depth ($Z_{320\text{ nm }1\%}/Z_{\text{max}}$) was high enough (between 10-100%)

so that harmful effects to organisms are likely. A similar observation has also been reported for some lakes in our study region in the studies by Rautio & Korhola (2002 a; b). In 12 of 18 lakes > 1% of PAR reached the bottom having an important consequence for the total primary productivity of these systems; in many transparent, oligotrophic northern lakes >50% of the total system (pelagic plus benthic) primary production is confined to the bottom (Björk-Ramberg & Ånell 1985, Rautio *et al*., 2011).

Thawing permafrost and transformations of mires and wetlands that are consequences of warming temperatures (IPCC 2013) have an important influence for the solar attenuation. Also the more subtle changes in catchment characteristics related to changes in vegetation cover will modify DOM in the receiving water bodies. Our data show a strong Kd UVB response to small changes in CDOM and suggest that even minor shifts in CDOM quality may largely change the UV radiation exposure of transparent high latitude lakes with likely consequences on biota. Similar responses will occur for Kd PAR, however, the changes may not be large enough to cause major shifts in the relative importance of pelagic and benthic primary production in the studied lakes that are currently illuminated to the bottom due to the combination of shallow lake depth and low CDOM concentration and color.

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Table I. Catchment and morphological parameters, temperature, water chemistry and algal parameters of the study lakes. Altitude above sea level (Alt a.s.l.; m), maximum lake depth (Max depth; m), lake area (ha), catchment area (Catch area; ha), catchment to lake area (C to L area), catchment slope (C slope; mean %), temperature (T; °C), pH, alkalinity (Alk; mmol l^{-1}), conductivity (Cond; mS m^{-1}), ammonium (NH_4; µg l^{-1}), nitrate and nitrite (NO_{3+2}; µg l^{-1}), phosphate (PO_4; µg l^{-1}), total nitrogen (TN, µg l^{-1}), total phosphorus (TP; µg l^{-1}), silica (SiO_2; µg l^{-1}), turbidity (Turb; FNU), chlorophyll-a (Chl; µg l^{-1}) and phytoplankton biomass (Phyto biom; mg l^{-1}).

Lake (code)	Alt a.s.l.	Max depth	Lake area	Catch area	C to L area	C slope	T	pH	Alk	Cond	NH_4	NO_{3+2}	PO_4	TN	TP	SiO_2	Turb	Chl	Phyto biom
Mountain birch woodland (MBW)																			
Kilpisjärvi (NF000K)	473	57	3710	27100	7	8	11.9	7.2	0.172	2.6	6.0	14.0	<2	100	6	1.2	0.2	0.61	0.11
Kilpisjärvi 30 m							8.7	7.7	0.165	2.6	12.0	26.0	<2	140	5	1.3	0.2	0.13	0.04
Korsajärvi (NF0356)	528	2	20	212	11	2.9	7.1	6.9	0.102	1.3	7.0	<2	<2	320	13	3.0	0.9	2.38	0.42
Ristijärvi (NF0354)	571	2	11	32	3	2.2	7.2	5.6	0.017	0.4	<5	<2	<2	220	7	0.4	0.5	0.67	0.41
Koddojavri (NF0344)	571	2	5	56	11	2.7	7.3	5.3	0.021	0.9	7.0	4.0	<2	410	11	2.7	0.7	1.08	0.17
Shrub tundra (ST)																			
Mallalampi (NF000M)	602	4	1	42	42	6.7	9.7	7.4	0.186	2.5	<5	3.0	<2	96	4	4.4	0.2	0.34	0.08
Lake 613 (NF0026)	613	5	15	396	26	7.5	10.2	7.2	0.107	1.6	<5	<2	2.0	120	11	3.2	0.3	0.57	0.06
Saanajärvi (NF0009)	679	24	70	525	8	13.1	11.7	6.8	0.181	3.2	<5	<2	<2	110	5	1.1	0.2	0.75	0.07
Saanajärvi 16 m							7.1	7.0	0.181	3.4	8.0	17.0	<2	120	5	1.2	0.2	0.71	0.07
Masehjavri (NF0016)	680	11	17	158	10	4.4	8.8	7.3	0.132	1.6	<5	<2	<2	140	6	2.4	0.3	0.45	0.11
Peeralampi (NF0076)	696	7	25	414	17	6.5	10.3	7.2	0.128	2.0	<5	<2	<2	130	7	3.5	0.4	0.96	0.17
Toskaljärvi (NF0202)	704	22	100	1338	13	9.1	8.5	7.8	0.392	4.3	<5	4.0	<2	74	7	1.5	0.3	0.36	0.14
Somaslompolo	760	10	16	163	10	7.2	7.7	7.4	0.172	3.1	5.0	4.0	<2	85	8	2.2	0.4	0.87	0.18

(NF0223)																			
Kohpejavri (NF0108)	774	4	21	220	11	7.0	6.5	7.3	0.099	1.5	<5	<2	<2	120	5	2.8	0.3	0.28	0.16
Mallajärvi (NF0002)	776	13	17	118	7	10.3	10.6	6.7	0.050	0.7	<5	3.0	<2	81	6	1.5	0.3	0.71	0.06
Mallajärvi 8 m							10.2	6.8	0.047	3.5	<5	4.0	<2	79	5	1.5	0.3	0.69	0.14
Porevarri (NF0261)	794	6	11	166	15	4.4	7.2	7.4	0.213	3.6	<5	<2	<2	110	9	2.9	0.5	0.86	0.31
Barren tundra (BT)																			
Kuorroladdu (NF0221)	900	9	6	45	10	5	5.9	7.3	0.106	2.6	<5	2.0	<2	71	7	0.9	0.3	0.44	0.09
Vuobmegasvarri (NF0099)	900	4	1	39	32	10.6	7.5	6.9	0.108	1.5	6.0	<2	<2	120	6	2.5	0.5	0.44	0.11
Lake 1009 (NF0033)	1009	12	10	98	10	6.5	8.8	5.8	0.011	0.4	<5	4.5	<2	72	4	2.5	0.1	0.16	0.03
Stuorralampi (NF000S)	1024	2	1	4	4	2	6.7	6.8	0.057	1.9	<5	4.0	<2	85	3	1.0	0.3	0.21	0.04

Table II. DOC and DOM characteristics of the study lakes. Dissolved organic carbon (DOC; mg l^{-1}), absorption coefficient of dissolved organic matter at 440 nm (a_{440}; m^{-1}), absorption coefficient at 320 nm (a_{320}; m^{-1}), a_{320} divided by the DOC concentration (a^*_{320}; mg^{-1} m^{-1}), UV absorbance at 254 nm measured in inverse meters divided by the DOC concentration (SUVA, mg^{-1} m^{-1}), spectral slope for light absorption by DOM calculated on wavebands 300-650 nm, 275-295 nm and 350-400 nm (S; nm^{-1}), ratio of $S_{275-295}$ to $S_{350-400}$ (S_R), spectral slope at 280 and 390 nm (S280, S390), percentage of the integrated area of low (%LMW), medium (%MMW) and high (%HMW) molecular weight compounds from total integrated area under the synchronous fluorescence spectrum, ratio of fluorescence integrated over the waveband 280-323 nm (Lλ/Hλ) and 433-595 nm (Mλ/Hλ) to that over the waveband 433-595 nm and humification index (HI). Nd = no data.

Lake (code)	DOC	a_{440}	a_{320}	a^*_{320}	SUVA	$S_{300-650}$	$S_{275-295}$	$S_{350-400}$	S_R	S280	S390	%LMW	%MMW	%HMW	Lλ/Hλ	Mλ/Hλ
Mountain birch woodland (MBW)																
Kilpisjärvi (NF000K)	2.7	0.5	3.3	1.2	1.55	0.0166	0.0186	0.0127	1.5	0.0175	0.0169	24.0	48.5	27.5	0.9	1.8
Kilpisjärvi 30 m	2.2	0.5	3.1	1.4	1.82	0.0165	0.0187	0.0125	1.5	0.0186	0.0169	14.9	45.4	39.7	0.4	1.1
Korsajärvi (NF0356)	13.8	4.8	34.3	2.5	2.46	0.0156	0.0142	0.0167	0.9	0.0140	0.0172	18.7	43.0	38.3	0.5	1.1
Ristijärvi (NF0354)	6.1	0.9	6.6	1.1	1.25	0.0163	0.0173	0.0155	1.1	0.0169	0.0169	23.6	39.1	37.3	0.6	1.0
Koddojavri (NF0344)	16.2	9.4	61.0	3.8	6.16	0.0150	nd	0.0164	2.2	0.0180	0.0167	nd	nd	nd	nd	nd
Shrub tundra (ST)																
Mallalampi (NF000M)	2.8	0.6	4.1	1.5	0.94	0.0159	0.0173	0.0133	1.3	0.0166	0.0168	18.6	42.3	39.2	0.5	1.1
Lake 613 (NF0026)	6.9	0.8	5.7	0.8	0.98	0.0160	0.0174	0.0150	1.2	0.0166	0.0176	16.5	44.8	38.7	0.4	1.2
Saanajärvi (NF0009)	3.3	0.6	3.6	1.1	1.42	0.0164	0.0186	0.0140	1.3	0.0176	0.0166	19.9	44.7	35.4	0.6	1.3
Saanajärvi 16 m	3.0	0.5	3.6	1.2	1.49	0.0161	0.0179	0.0128	1.4	0.0173	0.0168	15.3	52.3	32.4	0.5	1.6
Masehjavri (NF0016)	4.0	1.1	7.7	1.9	2.18	0.0159	0.0167	0.0152	1.1	0.0162	0.0171	15.5	45.6	38.9	0.4	1.2
Peeralampi (NF0076)	3.6	1.0	6.6	1.9	2.08	0.0156	0.0161	0.0145	1.1	0.0155	0.0166	14.4	48.8	36.8	0.4	1.3
Toskaljärvi	1.5	0.3	1.8	1.2	1.47	0.0152	0.0176	0.0085	2.1	0.0168	0.0155	23.0	39.2	37.8	0.6	1.0

(NF0202)																
Somaslompolo (NF0223)	2.5	0.3	1.0	0.4	0.56	0.0087	0.0190	0.0047	4.0	0.0179	0.0100	24.2	39.4	36.4	0.7	1.1
Kohpejavri (NF0108)	3.3	0.7	4.3	1.3	1.54	0.0156	0.0175	0.0142	1.2	0.0168	0.0163	18.5	45.1	36.4	0.5	1.2
Mallajärvi (NF0002)	2.4	0.3	1.9	0.8	0.94	0.0150	0.0170	0.0107	1.6	0.0167	0.0149	18.3	41.5	40.2	0.5	1.0
Mallajärvi 8 m	2.4	0.3	1.8	0.8	0.89	0.0154	0.0171	0.0107	1.6	0.0170	0.0155	13.2	41.4	45.5	0.3	0.9
Porevarri (NF0261)	2.7	0.6	3.4	1.3	1.51	0.0156	0.0167	0.0135	1.2	0.1063	0.0161	22.4	41.1	36.6	0.6	1.1
Barren tundra (BT)																
Kuorroladdu (NF0221)	1.9	0.2	nd	nd	0.43	nd	nd	nd	nd	0.0141	0.0155	25.0	51.0	23.9	1.0	2.1
Vuobmegasvarri (NF0099)	2.6	0.8	5.1	2.0	2.24	0.0155	0.0159	0.0148	1.1	0.0156	0.0166	20.5	41.8	37.7	0.5	1.1
Lake 1009 (NF0033)	1.6	0.1	nd	nd	0.26	nd	nd	nd	nd	0.0255	nd	13.6	36.6	49.8	0.3	0.7
Stuorralampi (NF000S)	2.2	0.3	1.6	0.7	0.86	0.0140	0.0173	0.0087	2.0	0.0168	0.0137	22.0	37.1	40.9	0.5	0.9

Table III. PAR and UV characteristics in the lakes. K_d vertical attenuation coefficient for downward photosynthetically active radiation (K_d PAR; m^{-1}) and at 320 nm (K_d 320; m^{-1}), attenuation depth of UV expressed as a proportion of lake maximum depth ($Z_{320\ 1\%}/Z_{max}$, %), 1% PAR depth, 1% UVB depth and 1% depth of 320 nm UV relative to the 1% depth of PAR (Transparency ratio)

Lake (code)	K_d PAR	K_d 320	$Z_{320\ 1\%}$/Z max	1% PAR depth	1% UVB depth	Transparency ratio
Mountain birch woodland (MBW)						
Kilpisjärvi (NF000K)	0.2	3.1	3	19.1	1.5	7.7
Korsajärvi (NF0356)	2.6	41.0	5	1.8	0.1	6.2
Ristijärvi (NF0354)	0.7	7.3	25	Bottom	0.6	10.0
Koddojavri (NF0344)	2.4	70.4	5	1.9	0.1	3.5
Shrub tundra (ST)						
Mallalampi (NF000M)	0.5	3.7	20	Bottom	1.2	12.6
Lake 613 (NF0026)	0.6	6.3	10	Bottom	0.7	9.6
Saanajärvi (NF0009)	0.3	4.1	4	16.4	1.1	6.9
Masehjavri (NF0016)	0.5	7.1	4	10.2	0.6	6.3
Peeralampi (NF0076)	0.5	7.7	7	Bottom	0.6	6.5
Toskaljärvi (NF0202)	0.3	2.2	8	16.4	2.1	12.8
Somaslompolo (NF0223)	0.2	1.2	30	Bottom	3.8	17.2
Kohpejavri (NF0108)	0.6	5.1	20	Bottom	0.9	10.7
Mallajärvi (NF0002)	0.3	1.8	13	Bottom	2.6	13.9
Mallajärvi 8 m						

Porevarri (NF0261)	0.4	3.6	17	Bottom	1.3	9.9
Barren tundra (BT)						
Kuorroladdu (NF0221)	0.1	0.6	56	Bottom	7.8	15.2
Vuobmegasvarri (NF0099)	0.6	5.9	15	Bottom	0.8	9.3
Lake 1009 (NF0033)	0.2	0.3	100	Bottom	Bottom	50.9
Stuorralampi (NF000S)	0.4	2.1	100	Bottom	Bottom	20.7

Table IV. Combination of environmental variables, taken *k* at the time, giving the largest rank correlation p_s, between environmental and light parameter similarity matrices. Bold indicates best combination overall. a440: absorbance at 440 nm, S280: spectral slope at 280 nm, DOC: dissolved organic carbon, SUVA: UV absorbance at 254 nm measured in inverse meters divided by the DOC concentration, S390: spectral slope at 390 nm HI: humification index, and chl: chlorophyll-a.

k	Best variable combinations (p_s)						
1	a440 (0.73)	S280 (0.54)	DOC (0.49)	SUVA (0.49)	S390 (0.46)	HI (0.39)	Chl (0.39)
2	**a440, S390** **(0.87)**						
3	a440, S390, S280 (0.81)						
4	DOC, a440, S390, S280 (0.79)						
5	DOC, SUVA, HI, a440, S390 (0.80)						

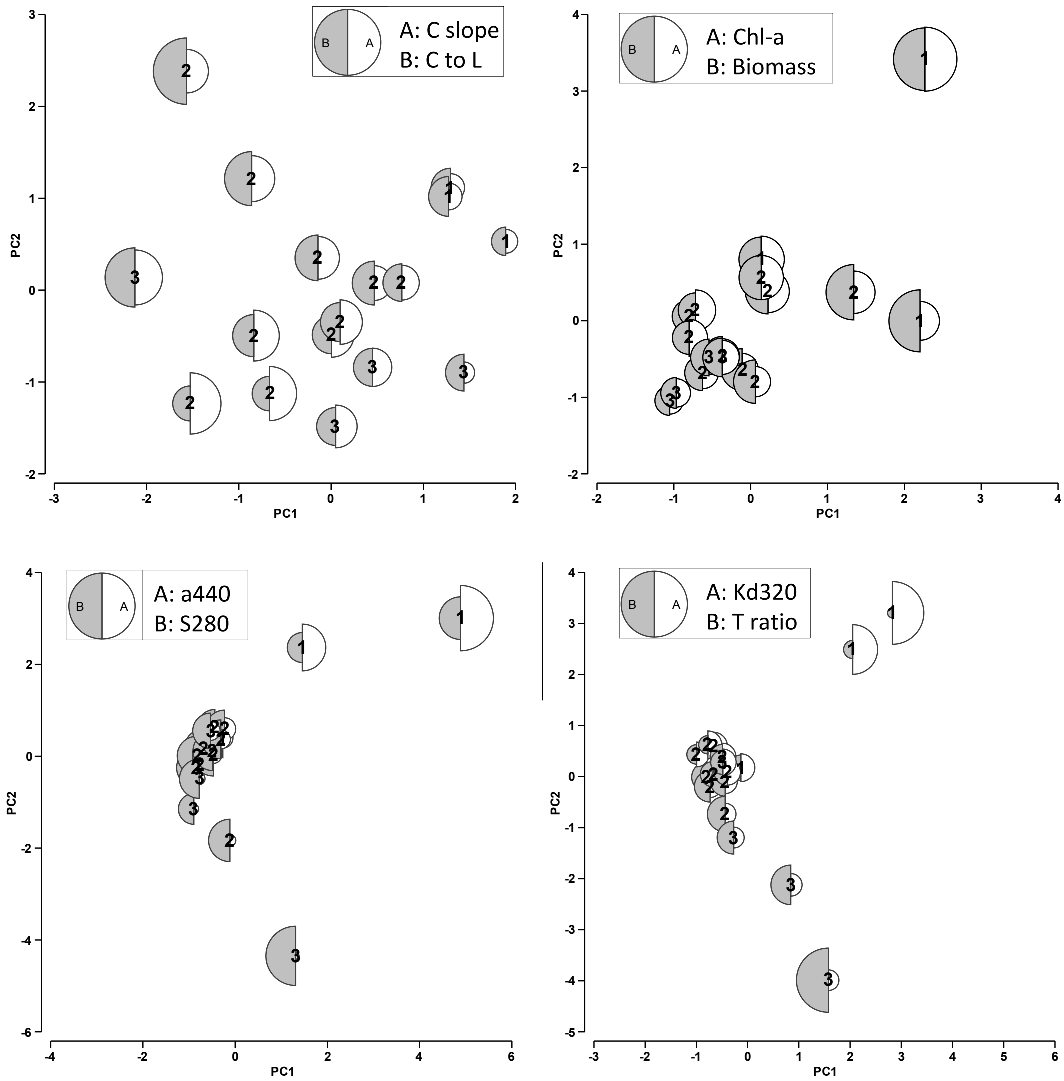
Figure captions

Figure 1. Map of the area showing the study sites and vegetational zones. Lakes located in the barren tundra are marked with black dots, lakes in shrub tundra with white dots and lakes in mountain birch woodland with grey dots.

Fig. 2. Segmented bubble plot PCA ordinations for a) catchment and morphological parameters, b) phytoplankton, c) CDOM characteristics and d) UV and PAR attenuation. Segment sizes are proportional to the values of catchment slope (C slope), catchment to lake ratio (C to L), chl-a concentration (chl-a), phytoplankton biomass (Biomass), absorption coefficient at 440 nm (a440), spectral slope at 280 nm (S280), diffuse attenuation coefficient for UV-B (Kd_{320}) and transparency ratio (T ratio) in different lakes. The numbers indicate vegetation zones. 1: mountain birch woodland (MBW), 2: shrub tundra (ST) and 3: barren tundra (BT).

Figure 3**.** a) Spectral slope curves for absorption measurements and b) synchronous fluorescence spectroscopy scans of CDOM of lakes from barren tundra (Mallajärvi), shrub tundra (Lake 613) and mountain birch woodland (Korsajärvi). Spectral slopes are also shown for DOM from a bog and a *Scenedesmus* sp. phytoplankton culture to indicate differences between allochthonous and autochthonous carbon sources. Breaks in lines are for values that did not meet the regression coefficient requirement r2 > 0.95 (see methods for explanation).

Figure 4. Relationship between absorption coefficient at 440 nm (a440) and different light parameters: diffuse attenuation coefficient for UV-B (Kd_{320}) and PAR (Kd_{PAR}), and for the transparency ratio



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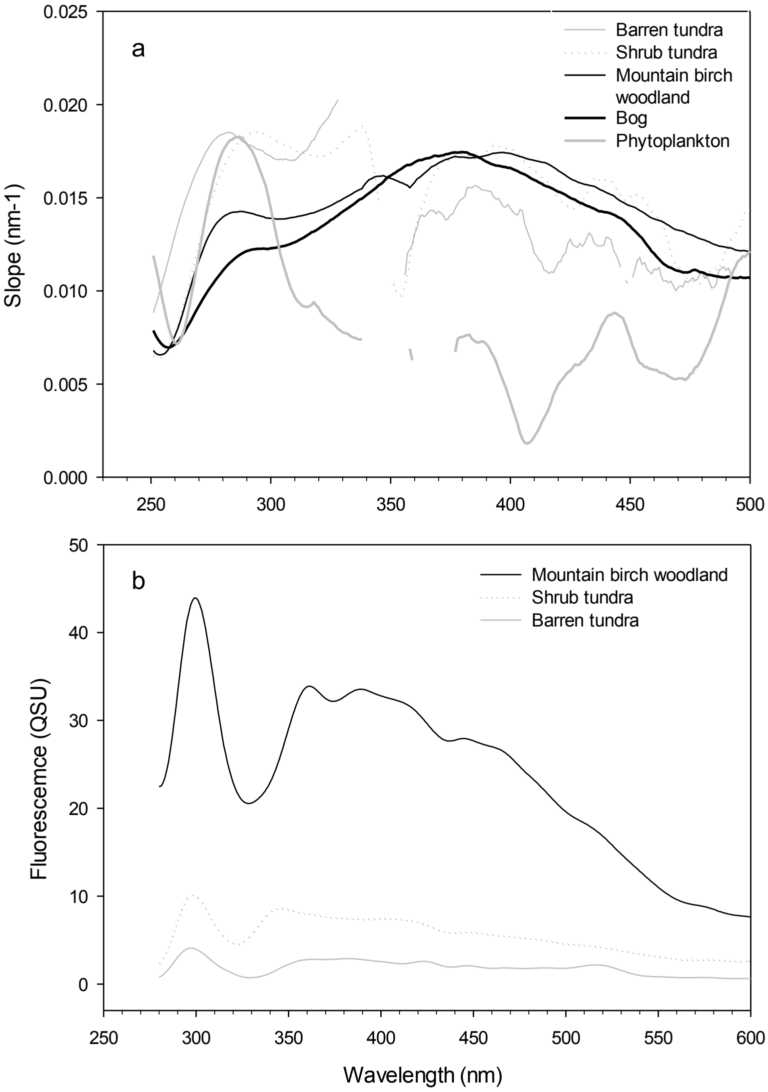

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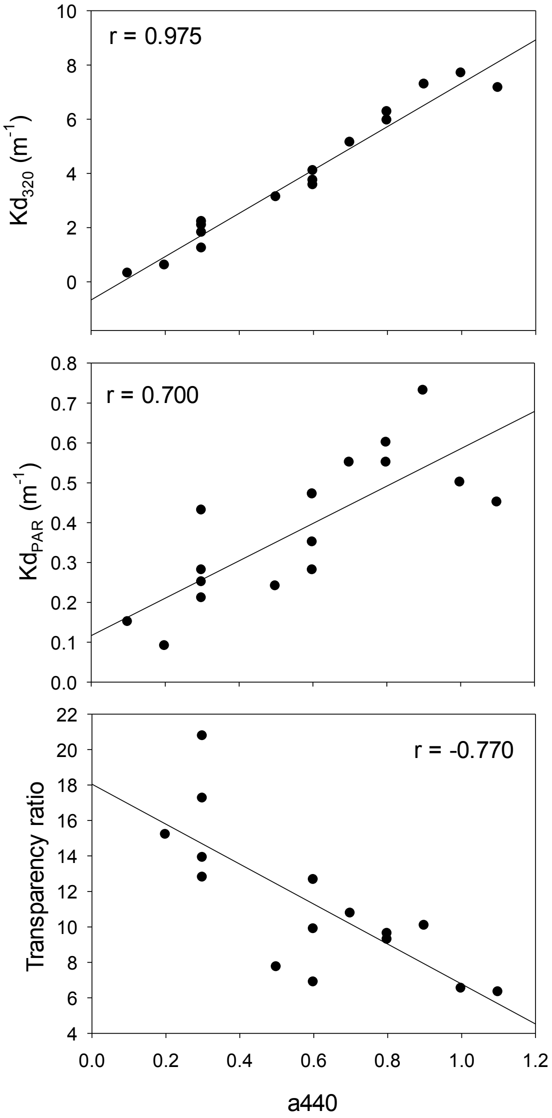

Fig. 4. Relationship between absorption coefficient at 440 nm (a440) and different light parameters: diffuse attenuation coefficient for UV-B (Kd_{320}) and PAR (Kd_{PAR}), and the transparency ratio